COMPACT TOROID TRANSLATION WITH RELEVANCE TO PLASMA FLOW SWITCHING

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Numerous experiments involving the generation and translation of compact toroid magnetized plasmas in straight and conical compression geometries have been performed at the Phillips Laboratory. The SHIVA STAR fast capacitor bank (1300 µF, 3 nH, 30 kV - 120 kV) has been used, with additional series inductance (~50 nH), to deliver multi-megampere currents to the CT plasmas and drive them through coaxial vacuum electrode gaps of approximately 1 meter length. Traditional B-dot probes in the gap have provided spatially localized time histories of both the driving toroidal, and CT internal poloidal and toroidal, magnetic fields. From these measurements we have been able to assess the applicability of such translating plasmas as long-conduction-time plasma flow switches, and to design an experimental demonstration of their effectiveness in conjunction with a pulsed-gas dense-plasma-focus (DPF) load. In this paper we summarize relevant results from our previous experiments and present design information and 2½-D MHD supporting calculations for a CT-switched DPF demonstration experiment.

Introduction

For several applications, such as the production of high-power x-ray pulses using plasma implosions, the characteristic current risetime of the primary electrical energy system (*i.e.*, capacitor bank or magnetic flux compression generator) is too long. For example, fast z-pinches usually perform better with characteristic current risetimes of 100 ns, whereas low-inductance capacitor banks with more than 1 MJ energy storage are inherently limited to current risetimes in excess of 1 μs when directly coupled. Of course, considerable progress has been made in high-power pulsed-power systems using multi-stage storage and switching elements; but in these systems, penalties are paid in terms of efficiency, size, complexity, and cost. Therefore, it would be highly desirable to reduce the direct output current risetime from greater than 1 μs to less than 100 ns with a single, controllable switch.

One type of switch, which is generally restricted to the last stage of electrical pulse compression, is the so-called plasma opening switch, or POS. This element, created by injecting plasma across a vacuum electrode gap in parallel with the load, acts as a low-impedance path until its continuity is effectively broken due to instability and resistivity growth.

Although the POS has been generally successful in terms of fast opening time and generation of high voltage (> 1 MV), it has been disappointing in terms of conduction time (typically, $t_c < 0.5$ μs) for currents of interest. Furthermore, prediction of its operation has had limited success. By contrast, plasma flow switches[1] operate by translating a plasma armature from a current initiation

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location to a load region, as shown in Fig. 1. With proper design (*i.e.*, selection of proper armature mass for given driver electrical characteristics and geometry) it is possible to arrange for time of current peak to coincide with arrival of the current sheath at the load. In this type of operation, the current risetime at the load is given, not by the characteristic driver risetime, but rather the length of the load plus the thickness of the current sheath divided by the velocity of the current sheath.

The PFS has been investigated at several laboratories. At Phillips Lab, successful PFS discharges have been conducted on the SHIVA STAR capacitor bank, with peak current transfer rates in excess of 10^{13} A/s, conduction times of several microseconds, and load current of 10 MA rising in less than 500 ns.[2] These experiments clearly demonstrated the efficacy of the PFS at high currents and long conduction times.

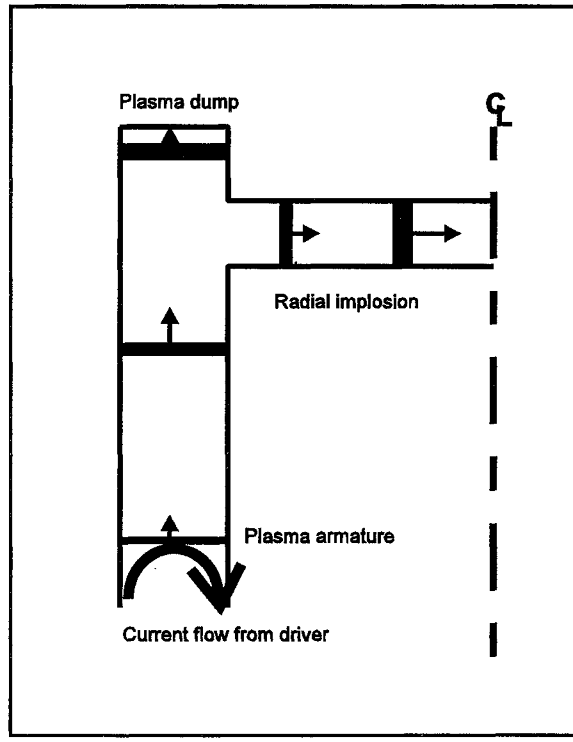

Figure 1 Basic PFS scheme is simple and intuitive.

In spite of the successful PFS experiments on SHIVA STAR, other long-conduction-time, high-current experiments have not been as successful. It is known that the PFS plasma armature is unstable to the Rayleigh-Taylor instability, and 2-D MHD simulations show that armature mass is laid down against the electrodes. The R-T instability results in effective thickening of the current sheath, at a minimum, and in uncontrolled current disruption (POS behavior) at advanced nonlinear stages of development. The material deposited along the electrodes or thrown ahead by the R-T instability can potentially make its way into the load region. This, in turn, can lead to severely Alfvén-limited flux delivery and significant load mass accretion. Finally, residual material left in the wake of the armature eventually causes upstream shunting of the current.

Compact Toroid Plasma Flow Switch

A compact toroid (CT) is an annular low-beta plasma configuration with entrained toroidal and poloidal magnetic fields sustained by internal poloidal and toroidal currents.[3] Such configurations have been studied analytically, computationally, and experimentally. Once created, they have been found to naturally relax to a near-minimum-free-energy state that is incredibly robust and stable to ideal and resistive MHD modes. Because of this stability, they were proposed as armatures in coaxial plasma gun geometry for a variety of applications, including plasma flow switching[4] (Fig. 2).

The CTPFS has a number of distinct advantages over the more conventional unmagnetized PFS. First, since the CT is stable, very long conduction times can be achieved - limited essentially by the resistive decay of the internal magnetic fields. Second, since the plasma is effectively contained within its own magnetic bag, mass deposition along the electrodes or into the load is significantly inhibited. Furthermore, the intrinsic "magnetic insulation" diminishes thermal conduction from the

plasma to the electrodes, reducing desorption or evaporation of material into the electrode gap. Finally, since work must be done to compress the internal CT fluxes in converging geometries, an additional tuning parameter (besides armature mass) is available to control the armature trajectory.

We have been investigating compact toroids in our laboratory for several years.[5] More recent experiments have assessed the dynamics of CT armatures in converging coaxial geometries at acceleration capacitor bank stored energies up to 1.1 MJ.[6]

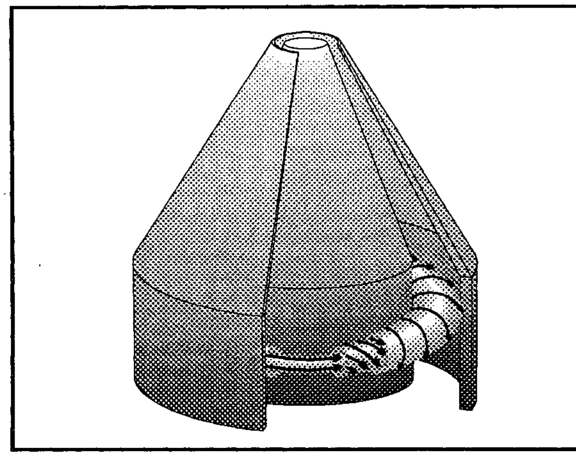

Figure 2 CTPFS is basically a coaxial plasma gun with magnetized CT armature.

During these experiments, conduction times of CT armatures with full current delivery (in excess of 1 MA) up to 15 μs were achieved over translation distances in excess of 1 m (both limited only by electrode length). The geometry used in these experiments is shown in Fig. 3. Here one can see the outer vacuum vessel, inner and outer coaxial electrodes, and ancillary CT formation hardware components at the bottom of the figure. Also shown are various radial diagnostic ports, used primarily for inductive (B-dot) probes. These probes are inserted into the electrode gap and measure the local time histories of the passing CT internal magnetic fields, as well as the toroidal magnetic field behind the CT associated with the acceleration discharge.

To ascertain the suitability of the translating CT as a plasma flow switch, we observed the rise of current at various axial and azimuthal positions. Indications of good performance are rapid rise and azimuthal simultaneity. In Fig. 4 we show a typical overlay of driver (acceleration discharge) current and current inferred from two probes 180 degrees apart at the C7 axial station (furthest downstream in the conical section). One can see that the risetime to greater than 60% of the driver current (1.5 MA) is less than 500 ns, and that both azimuthal probe signals are simultaneous to within less than 100 ns. This represents an order of magnitude reduction in current risetime downstream. Parameters for this experiment were C = 440 μF, V_0 = 70 kV (1.1 MJ stored energy), and 1 mg CT plasma armature mass. Initial CT internal magnetic field energy was approximately 10 kJ.

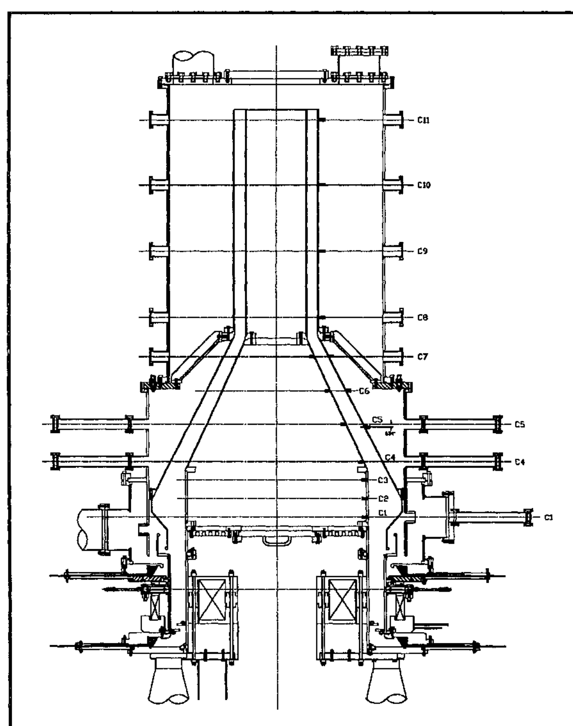

Figure 3 3X non-self-similar radial compression hardware used to study CT dynamics and PFS-related power flow.

In addition to rapid current rise and azimuthal simultaneity, reliable and reproducible behavior is also desirable. In our experiments, we

have found that the motion of the CT armatures is extremely reproducible. For example, in Fig. 5 we show an overlay of the histories of the axial component of the internal CT poloidal magnetic field for a particular downstream probe as recorded on three successive shots spanning 5 days. One can see that the timing is essentially indistinguishable, and even that the peak field amplitudes are equal to within ±10 %.

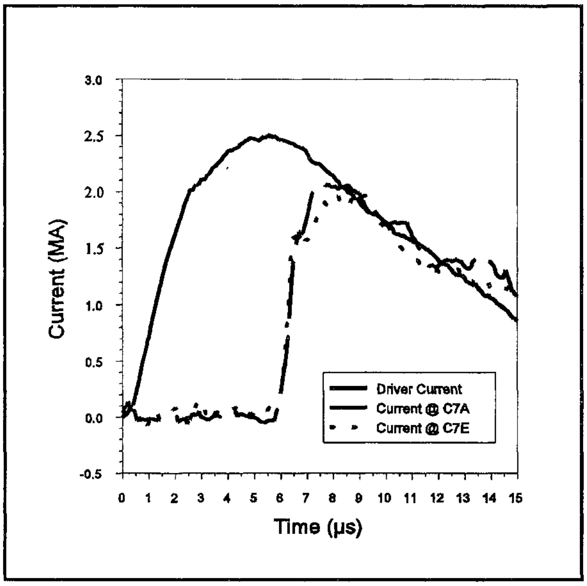

Figure 4 Overlay of driver current and two downstream probe currents 180° apart.

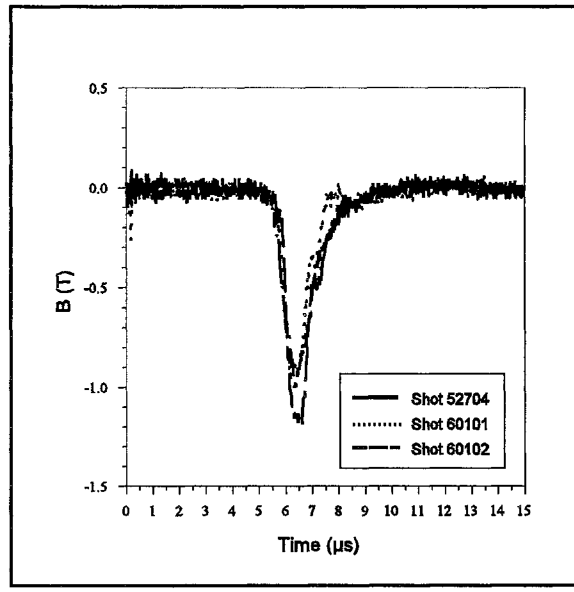

Figure 5 Overlay of axial component of CT poloidal field for three successive shots over five days.

CTPFS-DPF Experiment

The above measurements suggest that if a radial implosion load were situated at the probe location, high-quality implosions could be driven. In order to demonstrate current delivery to a real implosion load via CTPFS operation, we have designed a gas-puff plasma focus load experiment. The concept is illustrated in Fig. 6. Here the CTPFS armature simply replaces the snowplow run-down portion of a conventional Mather-type DPF.[7] When the CT exits the conical electrodes the current sheath is in position to drive a radial gas implosion to pinch. The actual experiment makes use of existing hardware which has been successfully operated at the megajoule stored energy level.

One reason for choosing this type of load is that previous DPF experiments have had

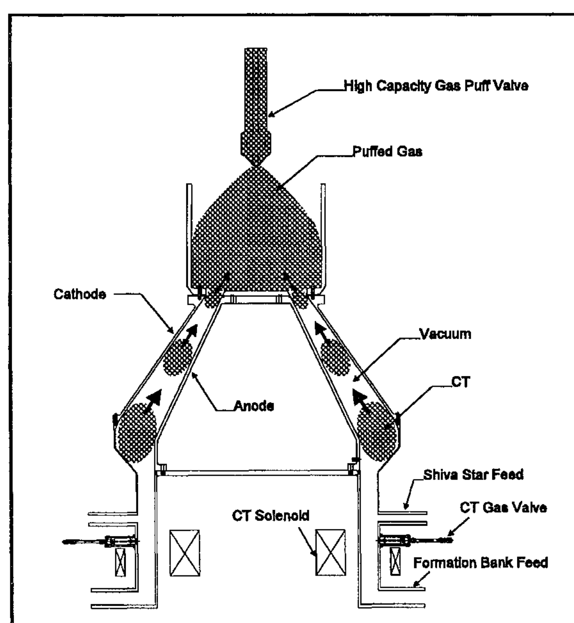

Figure 6 CTDPF experiment schematic.

difficulty operating above 1 MJ discharge energy, or 2 MA - 3 - MA current. One contributing factor is a tendency to break down the vacuum insulator. We believe that the combination of puffing the load gas into the chamber and translating the current sheath to that load far away from a well-shielded insulator may lead to successful DPF operation at the multi-megajoule, multi-megampere level.

Selected 2½-D MHD simulations of the experiment have been performed using the MACH2 code.[8] The simulation grid and initial puffed neon gas neutral density distribution are shown in Fig. 7. For the results presented here the peak initial mass density was 1 kg/m^3 and the initial temperature was 300 K. The delay between firing of the gas valve and CT formation was 500 μs. The acceleration (SHIVA STAR) capacitor bank was charged to 2 MJ. The CT was formed by a 350 kJ discharge through 1.5 mg of injected neon. Figs. 8a and 8b show the calculated current density vectors and ion isodensity contours for a time corresponding to radial current sheath implosion following exit of the CT from the cones, 7 μs after the beginning of the main SHIVA STAR discharge. One can see that a radially imploding sheath has indeed formed. In the simulations the current rises to roughly 3 MA in 350 ns at the top of the inner electrode.

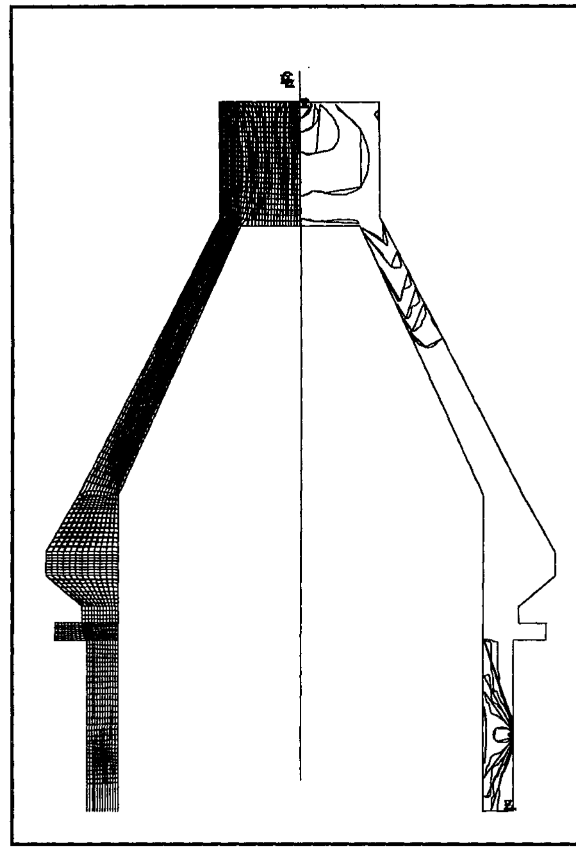

Figure 7 MACH2 computational grid and neutral gas isodensity contours at time of CT formation discharge.

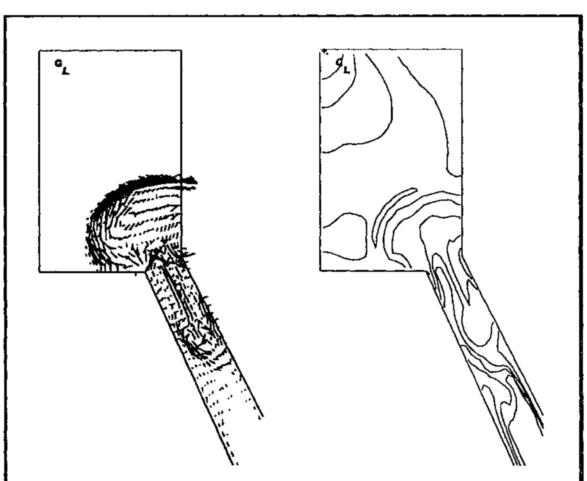

Figure 8 Current density vectors (a) and ion isodensity contours (b) 7 μs after main current discharge.

Conclusion

Progress has been made in the development of plasma flow switches which have the capability of reducing the inherent risetime of capacitor banks or explosive flux compression generators from multi-microseconds to sub-microsecond, at multi-megampere currents. Measurements of the risetime, azimuthal simultaneity, and especially reproducibility of magnetized compact toroid plasma armatures have shown reproducible, highly symmetric, fast-rising, multi-megampere currents can be delivered to an implosion load.

Based on these measurements, a demonstration experiment has been designed

which uses a compact toroid plasma flow switch to initiate a plasma focus discharge. The experiment is designed for operation at up to 2 MJ of stored discharge energy and currents up to 3 MA. Magnetohydrodynamic simulations of the experiment using neon as the armature as well as the load gas indicate that full current is delivered to the load region with a risetime of approximately 350 ns, and subsequent radial implosion of the current sheath is observed.

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